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Dual Grid Voltage Modulated Direct Power Control of Grid-Connected Voltage Source Converter under Unbalanced Network Condition

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***Abstract*—The Grid voltage Modulated Direct Power Control (GVM-DPC) for Voltage Source Converter (VSC) is a recently proposed superior control strategies which features several advantages such as fast power reference tracking, simple structure, no need to use synchronizing techniques, strong robustness and so on. In this paper, an improved Dual Grid Voltage Modulated Direct Power Control (D-GVM-DPC) strategies for unbalanced grid voltage condition is proposed and compared with regular voltage oriented dual PI control techniques. The idea of this improvement is to separately control the positive and negative sequence power components based on the original GVM-DPC controller. The simulation results shows that the proposed strategy is superior to the dual current control schemes been used with voltage oriented control strategy.**

***Index Terms*—Unbalance condition, Voltage Source Converters, Direct Power Control (DPC)**

I. Introduction

Voltage source converters (VSC) are widely used in modern renewalbe distributed power systems nowadays. As the newly constructed renewable energy sources are generally located in remote areas, the grid-connected VSCs must capable to deal with severe grid conditions, which put forward a high requirements for its performance [1].

Current control strategies of converters can be mainly classified into two categories: Voltage-Oriented Control (VOC) and Direct Power Control (DPC). In VOC strategies, the controller decomposes the currents into two components which represent the active and reactive powers and uses Proportional-Integral (PI) controllers to regulating them separately. The concept of Direct Power Control (DPC) strategy has been proposed for years, which features several advantages, the most prominent point is that it has a fast convergence rate when tracking the power reference values compare to VOC. Besides, the phase lock loop is no longer necessary for DPC strategy, therefore the controller is simpler than the classical VOC [2]–[6]. However, traditional Look-Up Table (LUT) based DPC structure has a obvious drawback. Because it uses hysteresis comparators to generate control signals, the switching frequency of controller is variable according to the state of operation, which will cause the harmonic spectrum of powers under steady state seriously [4].

G.Abad proposed a LUT-based predictive DPC technique for VSCs in doubly fed induction machine to resolve the problem [7]. Other solutions are mainly focus on modifying the generation of DPC control signal by using traditional Pulse Width Modulation (PWM). This type of solutions are widely proposed and discussed recently in many papers. [8] proposes an improved DPC for three-phase PWM rectifier with simple calculation. An nonlinear sliding-mode based DPC is proposed in [3]. backstepping control has been proposed for the DPC to improve its performance [9]. A dead-beat predictive strategy DPC for VSC is proposed and validated in [10].

Recently, a newly proposed DPC control strategy called Grid voltage modulated DPC (GVM-DPC) is proposed in [2], [4], [11]. The structure has several advantages such as fast dynamic response, simple structure and high robustness. The key point of the strategy is to transform the nonlinear system into a linear time-invariant system which simplifies the analysis of controlling unit considerably.

The improved DPC based strategies for unbalance grid condition are also discussed in many recent papers. [6] proposes an improved sliding mode control based DPC, by adding compensation terms into control signals, the ripples of output currents and powers can be restrained seperately. Relationship between 2 different DPC methods for PWM rectifiers under unbalance grid condition are discussed in [12].

However, GVM-DPC is a newly proposed control strategy thus its improvement for unbalanced gird condition is still limited. A improvement of GVM-DPC for unbalanced grid condition is proposed in [5], which select three power compensation objectives to cancel the negative sequence of output currents. This is a common practice to improve the performance of DPC under unbalanced voltage condition. In this paper, a newly designed solution for GVM-DPC to eliminate negative

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sequence components of currents is proposed. The main idea is applying dual power control schemes to GVM-DPC, which is similar to dual current control schemes been used with general VOC strategies. The positive and negative power sequences are separately calculated and controlled by two different controllers. The positive power sequence controller is designed to tracking the reference values of powers, and the negative power sequence controller is designed to eliminate the negative sequence of currents. The simulation results show that the proposed method can eliminate negative sequence components of currents under unbalanced grid conditions effectively.

The rest of paper is organized as follows, the mathematical modeling of converter under unbalanced condition is discussed in section II. In the section III, the design of proposed D-GVM-DPC is discussed. The simulation results are presented in the third section IV.

II. Mathematical Modeling of AC-side Under Unbalanced Grid Conditions

Consider a grid-connected voltage source inverter in stationary reference frame and take the inflow power direction as positive. The relationship between the phasors of grid voltage, gird current and inverter voltage in the stationary reference frame can be expressed as,

$$\boldsymbol{U}_{\mathrm{s}\alpha\beta} = R\boldsymbol{I}_{\mathrm{s}\alpha\beta} + L\frac{d\boldsymbol{I}_{\mathrm{s}\alpha\beta}}{dt} + \boldsymbol{V}_{\mathrm{c}\alpha\beta} \tag{1}$$

where $\boldsymbol{U}_{\mathrm{s}\alpha\beta}$, $\boldsymbol{I}_{\mathrm{s}\alpha\beta}$ and $\boldsymbol{V}_{\mathrm{c}\alpha\beta}$ are the grid voltage vector, the current vector and rectifier voltage vector respectively. L and R are the filter inductance and resistance respectively. The phasor under stationary reference frame can be expressed as two mutually perpendicular componentsas: $\boldsymbol{f}_{\mathrm{s}\alpha\beta} = f_{\mathrm{s}\alpha} + jf_{\mathrm{s}\beta}$. Futhermore, the grid voltage can be expressed as the sum of their respective positive and negative sequence components under unbalanced network conditions as,

$$\begin{aligned} &\boldsymbol{U}^{+}_{\mathrm{s}\alpha\beta} = u^{+}_{\mathrm{s}\alpha} + ju^{+}_{\mathrm{s}\beta},\ \boldsymbol{U}^{-}_{\mathrm{s}\alpha\beta} = u^{-}_{\mathrm{s}\alpha} + ju^{-}_{\mathrm{s}\beta} \\ &\boldsymbol{V}^{+}_{\mathrm{c}\alpha\beta} = v^{+}_{\mathrm{c}\alpha} + jv^{+}_{\mathrm{c}\beta},\ \boldsymbol{V}^{-}_{\mathrm{c}\alpha\beta} = v^{-}_{\mathrm{c}\alpha} + jv^{-}_{\mathrm{c}\beta} \\ &\boldsymbol{I}^{+}_{\mathrm{s}\alpha\beta} = i^{+}_{\mathrm{s}\alpha} + ji^{+}_{\mathrm{s}\beta},\ \boldsymbol{I}^{-}_{\mathrm{s}\alpha\beta} = i^{-}_{\mathrm{s}\alpha} + ji^{-}_{\mathrm{s}\beta} \end{aligned} \tag{2}$$

The positive and negative sequence voltage and current components in the stationary reference frame can be expressed as,

$$\begin{aligned} &u^{+}_{\mathrm{s}\alpha} = |\boldsymbol{U}^{+}_{\mathrm{s}}|cos(\omega_1 t + \phi^{+}_{\mathrm{u}}),\ u^{-}_{\mathrm{s}\alpha} = |\boldsymbol{U}^{-}_{\mathrm{s}}|cos(\omega_1 t + \phi^{-}_{\mathrm{u}}) \\ &u^{+}_{\mathrm{s}\beta} = |\boldsymbol{U}^{+}_{\mathrm{s}}|sin(\omega_1 t + \phi^{+}_{\mathrm{u}}),\ u^{-}_{\mathrm{s}\beta} = -|\boldsymbol{U}^{-}_{\mathrm{s}}|sin(\omega_1 t + \phi^{-}_{\mathrm{u}}) \\ &i^{+}_{\mathrm{s}\alpha} = |\boldsymbol{I}^{+}_{\mathrm{s}}|cos(\omega_1 t + \phi^{+}_{\mathrm{i}}),\ i^{-}_{\mathrm{s}\alpha} = |\boldsymbol{I}^{-}_{\mathrm{s}}|cos(\omega_1 t + \phi^{-}_{\mathrm{i}}) \\ &i^{+}_{\mathrm{s}\beta} = |\boldsymbol{I}^{+}_{\mathrm{s}}|sin(\omega_1 t + \phi^{+}_{\mathrm{i}})\ i^{-}_{\mathrm{s}\beta} = -|\boldsymbol{I}^{-}_{\mathrm{s}}|sin(\omega_1 t + \phi^{-}_{\mathrm{i}}), \end{aligned} \tag{3}$$

where $|\boldsymbol{U}^{+}_{\mathrm{s}}|$, $|\boldsymbol{U}^{-}_{\mathrm{s}}|$, $|\boldsymbol{I}^{+}_{\mathrm{s}}|$, $|\boldsymbol{I}^{-}_{\mathrm{s}}|$ are the amplitudes of positive and negative sequence components of grid voltages and currents respectively, ϕ^{+}_{u}, ϕ^{-}_{u}, ϕ^{+}_{i}, ϕ^{-}_{i} are the initial phase angle of positive and negative sequence components of grid voltages and currents respectively. Based on the (3), the positive and negative sequence variation of gird voltage and currents can be expressed as:

$$\begin{aligned} &\frac{du^{+}_{\mathrm{s}\alpha}}{dt} = -\omega_1 u^{+}_{\mathrm{s}\beta},\ \frac{du^{-}_{\mathrm{s}\alpha}}{dt} = \omega_1 u^{-}_{\mathrm{s}\beta} \\ &\frac{du^{+}_{\mathrm{s}\beta}}{dt} = \omega_1 u^{+}_{\mathrm{s}\alpha},\ \frac{du^{-}_{\mathrm{s}\beta}}{dt} = -\omega_1 u^{-}_{\mathrm{s}\alpha} \\ &\frac{di^{+}_{\mathrm{s}\alpha}}{dt} = -\omega_1 i^{+}_{\mathrm{s}\beta},\ \frac{di^{-}_{\mathrm{s}\alpha}}{dt} = \omega_1 i^{-}_{\mathrm{s}\beta} \\ &\frac{di^{+}_{\mathrm{s}\beta}}{dt} = \omega_1 i^{+}_{\mathrm{s}\alpha},\ \frac{di^{-}_{\mathrm{s}\beta}}{dt} = -\omega_1 i^{-}_{\mathrm{s}\alpha}, \end{aligned} \tag{4}$$

The active and reactive power can be expressed as,

$$P + jQ = \frac{3}{2}\boldsymbol{U}_{\mathrm{s}\alpha\beta} \times \boldsymbol{I}^{*}_{\mathrm{s}\alpha\beta} \tag{5}$$

where $\boldsymbol{I}^{*}_{\mathrm{s}\alpha\beta}$ is the conjugate of grid current. Substituting (2), (3) into (5), the instantaneous active and reactive power under unbalanced network can be calculated as follows,

$$\begin{cases} P = P_{11} + P_{12} + P_{21} + P_{22} \\ Q = Q_{11} + Q_{12} + Q_{21} + Q_{22}, \end{cases} \tag{6}$$

where P_{11} and Q_{11} are the respective components of active power and reactive power generated by positive components' interactions. P_{12}, Q_{12}, P_{21} and Q_{21} are the oscillating components at twice the network frequency generated by positive and negative components' interactions. P_{22} and Q_{22} are the components caused by negative components' interactions. They can be further expressed as follows,

$$\begin{bmatrix} P_{11} \\ P_{12} \\ P_{21} \\ P_{22} \\ Q_{11} \\ Q_{12} \\ Q_{21} \\ Q_{22} \end{bmatrix} = \begin{bmatrix} u^{+}_{\mathrm{s}\alpha} & 0 & u^{+}_{\mathrm{s}\beta} & 0 \\ 0 & u^{+}_{\mathrm{s}\alpha} & 0 & u^{+}_{\mathrm{s}\beta} \\ u^{-}_{\mathrm{s}\alpha} & 0 & u^{-}_{\mathrm{s}\beta} & 0 \\ 0 & u^{-}_{\mathrm{s}\alpha} & 0 & u^{-}_{\mathrm{s}\beta} \\ u^{+}_{\mathrm{s}\beta} & 0 & -u^{+}_{\mathrm{s}\alpha} & 0 \\ 0 & u^{+}_{\mathrm{s}\beta} & 0 & -u^{+}_{\mathrm{s}\alpha} \\ u^{-}_{\mathrm{s}\beta} & 0 & -u^{-}_{\mathrm{s}\alpha} & 0 \\ 0 & u^{-}_{\mathrm{s}\beta} & 0 & -u^{-}_{\mathrm{s}\alpha} \end{bmatrix} \begin{bmatrix} i^{+}_{\mathrm{s}\alpha} \\ i^{-}_{\mathrm{s}\alpha} \\ i^{+}_{\mathrm{s}\beta} \\ i^{-}_{\mathrm{s}\beta} \end{bmatrix}. \tag{7}$$

In conventional DPC method, the active and reactive powers are directly regulated to a constant value, which usually set as reference values while the grid is strictly balanced. However, if the network is unbalanced, following equations should be satisfied for conventional DPC to regulate both active and reactive power at its reference constant value at the same time,

$$\begin{aligned} P_{12} + P_{21} = 0 \\ Q_{12} + Q_{21} = 0. \end{aligned} \tag{8}$$

Substituting (3), (7) into (8) yields,

$$|\boldsymbol{U}^{+}_{\mathrm{s}}||\boldsymbol{I}^{-}_{\mathrm{s}}|\cos(2\omega_1 t + \phi_{\mathrm{d}}) = -|\boldsymbol{U}^{-}_{\mathrm{s}}||\boldsymbol{I}^{+}_{\mathrm{s}}|\cos(2\omega_1 t + \phi_{\mathrm{q}}) \tag{9}$$

$$|\boldsymbol{U}^{+}_{\mathrm{s}}||\boldsymbol{I}^{-}_{\mathrm{s}}|\sin(2\omega_1 t + \phi_{\mathrm{d}}) = |\boldsymbol{U}^{-}_{\mathrm{s}}||\boldsymbol{I}^{+}_{\mathrm{s}}|\sin(2\omega_1 t + \phi_{\mathrm{q}}), \tag{10}$$

where $\phi_{\mathrm{d}} = \phi^{+}_{\mathrm{u}} + \phi^{-}_{\mathrm{i}}$, $\phi_{\mathrm{q}} = \phi^{-}_{\mathrm{u}} + \phi^{+}_{\mathrm{i}}$ Equations (9) and (10) must be satisfied throughout the whole system operation.

According to (9)

$$\begin{aligned} &|\boldsymbol{U}^{+}_{\mathrm{s}}||\boldsymbol{I}^{-}_{\mathrm{s}}| = -|\boldsymbol{U}^{+}_{\mathrm{s}}||\boldsymbol{I}^{-}_{\mathrm{s}}| \\ &\cos(2\omega_1 \mathrm{t} + \phi_{\mathrm{d}}) = \cos(2\omega_1 \mathrm{t} + \phi_{\mathrm{q}}). \end{aligned} \tag{11}$$

According to (10),

$$\begin{aligned}&|\boldsymbol{U}_{\mathrm{s}}^{+}||\boldsymbol{I}_{\mathrm{s}}^{-}|=|\boldsymbol{U}_{\mathrm{s}}^{-}||\boldsymbol{I}_{\mathrm{s}}^{+}|\\&\sin(2\omega_1\mathrm{t}+\phi_{\mathrm{d}})=\sin(2\omega_1\mathrm{t}+\phi_{\mathrm{q}}).\end{aligned}\tag{12}$$

It is obvious that (11) and (12) cannot be satisfied simultaneously, in other words, to completely restrain the active power and reactive ripples at the same time is impossible. A widely adopted solution to overcome this problem is to adding the compensation terms at both active and reactive power references to meet different control targets. There are mainly three targets as follows, (1) to obtain sinusoidal and symmetrical currents; (2) to remove reactive power ripple; (3) to cancel active power ripple. The control strategy proposed in this paper is mainly used to meet target(1). As can be seen from (7), P_{22} and Q_{22} are generated by the interaction of voltage and currents negative sequences, which means the negative sequence components of currents can be eliminated if those two components are regulated to zero. The following section will further discuss how the proposed D-GVM-DPC strategy can achieve this object.

III. Design of Proposed D-GVM-DPC

The main idea of this method is based on the structure of GVM-DPC proposed in [4]. In order to guarantee that two sequences can be well regulated, it is necessary to independently control each sequence. The original controller is then substituted by two controllers: one for the positive-sequence powers and one for negative- sequence powers. The positive sequence controller is used generate a proper positive converter voltage vector to regulate the output active power and reactive power at its reference value, while the negative sequence controller is used to generate negative converter voltage vector to restrain the ripple of currents. By differentiating (7), the instantaneous active and reactive powers P_{11} and Q_{11} can be expressed as,

$$\begin{aligned}\frac{dP_{11}}{dt}&=\frac{3}{2}(\frac{du_{\mathrm{s}\alpha}^{+}}{dt}i_{\mathrm{s}\alpha^{+}}+\frac{du_{\mathrm{s}\beta}^{+}}{dt}i_{\mathrm{s}\beta^{+}}+\frac{di_{\mathrm{s}\alpha}^{+}}{dt}u_{\mathrm{s}\alpha^{+}}+\frac{di_{\mathrm{s}\beta}^{+}}{dt}u_{\mathrm{s}\beta^{+}})\\\frac{dQ_{11}}{dt}&=\frac{3}{2}(\frac{du_{\mathrm{s}\beta}^{+}}{dt}i_{\mathrm{s}\alpha^{+}}-\frac{du_{\mathrm{s}\alpha}^{+}}{dt}i_{\mathrm{s}\beta^{+}}+\frac{di_{\mathrm{s}\alpha}^{+}}{dt}u_{\mathrm{s}\beta^{+}}-\frac{di_{\mathrm{s}\beta}^{+}}{dt}u_{\mathrm{s}\alpha^{+}}).\end{aligned}\tag{13}$$

Substituting (1), (2) and (4) into (13), the dynamics of the instantaneous active and reactive powers P_{11} and Q_{11} can be obtained as follows,

$$\begin{aligned}\frac{dP_{11}}{dt}&=-\omega_1Q_{11}-\frac{R}{L}P_{11}+\frac{3}{2L}[|\boldsymbol{U}_{\mathrm{s}}^{+}|^2-(v_{\mathrm{c}\alpha}^{+}u_{\mathrm{s}\alpha}^{+}+v_{\mathrm{c}\beta}^{+}u_{\mathrm{s}\beta}^{+})]\\\frac{dQ_{11}}{dt}&=\omega_1P_{11}-\frac{R}{L}Q_{11}-\frac{3}{2L}(v_{\mathrm{c}\alpha}^{+}u_{\mathrm{s}\beta}^{+}-v_{\mathrm{c}\beta}^{+}u_{\mathrm{s}\alpha}^{+}).\end{aligned}\tag{14}$$

Define U_{P}^{+} and U_{Q}^{+} as the Voltage Modulated Regulation (VMR) inputs which can be expressed as,

$$\begin{aligned}U_{\mathrm{P}}^{+}&=v_{\mathrm{c}\alpha}^{+}u_{\mathrm{s}\alpha}^{+}+v_{\mathrm{c}\beta}^{+}u_{\mathrm{s}\beta}^{+}\\U_{\mathrm{Q}}^{+}&=v_{\mathrm{c}\alpha}^{+}u_{\mathrm{s}\beta}^{+}-v_{\mathrm{c}\beta}^{+}u_{\mathrm{s}\alpha}^{+}.\end{aligned}\tag{15}$$

By manipulating (14) and (15), the VMR inputs can be also expressed as,

$$\begin{aligned}U_{\mathrm{P}}^{+}&=\nu_{\mathrm{P}}-\frac{2L}{3}\omega_1Q_{11}+|\boldsymbol{U}_{\mathrm{s}}^{+}|^2\\U_{\mathrm{Q}}^{+}&=\nu_{\mathrm{Q}}+\frac{2L}{3}\omega_1P_{11},\end{aligned}\tag{16}$$

where ν_{P} and ν_{Q} are the new control inputs. The power regulation system can be transformed into a LTI system as,

$$\begin{aligned}\nu_{\mathrm{P}}^{+}&=\frac{2L}{3}(\frac{dP_{11}}{dt}+\frac{R}{L}P_{11})\\\nu_{\mathrm{Q}}^{+}&=\frac{2L}{3}(\frac{dQ_{11}}{dt}+\frac{R}{L}Q_{11}).\end{aligned}\tag{17}$$

There are various control methods could be designed to generate ν_{P} and ν_{Q}, for simplicity and reliability, the PI controllers $F_{\mathrm{p}}(s)$ for both components are designed as,

$$\begin{aligned}\nu_{\mathrm{P}}^{+}=&K_{\mathrm{p,P}}(P_{11}^{*}-P_{11})+K_{i,P}\int(P_{11}^{*}-P_{11})dt\\\nu_{\mathrm{Q}}^{+}=&K_{\mathrm{p,Q}}(Q_{11}^{*}-Q_{11})+K_{i,Q}\int(Q_{11}^{*}-Q_{11})dt.\end{aligned}\tag{18}$$

The method about how to properly select proportional and integral gains to determining the system' s natural frequency and damping factor is discussed in [2].

Finally, using the inversion of (15), voltage vector reference value of the positive sequence controller can be calculated as follows,

$$\begin{cases}v_{\mathrm{c}\alpha}^{+}=\dfrac{u_{\mathrm{s}\alpha}^{+}U_{\mathrm{P}}^{+}+u_{\mathrm{s}\beta}^{+}U_{\mathrm{Q}}^{+}}{|\boldsymbol{U}_{\mathrm{s}}^{+}|^2}\\v_{\mathrm{c}\beta}^{+}=\dfrac{u_{\mathrm{s}\beta}^{+}U_{\mathrm{P}}^{+}-u_{\mathrm{s}\alpha}^{+}U_{\mathrm{Q}}^{+}}{|\boldsymbol{U}_{\mathrm{s}}^{+}|^2}.\end{cases}\tag{19}$$

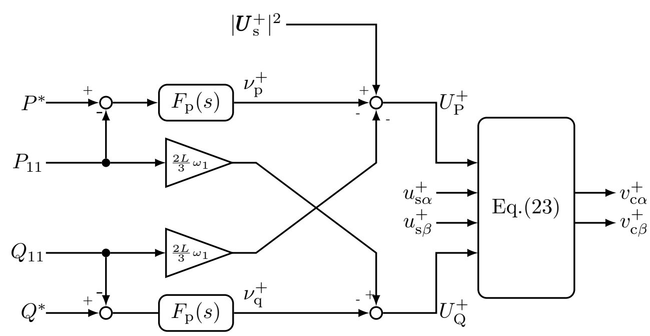

Fig. 1. Proposed UVM-DPC for positive sequence regulation.

As for the design of negative sequence controller, by differentiating (7) the instantaneous active and reactive power P_{22} and Q_{22} can be expressed as,

$$\begin{aligned}\frac{dP_{22}}{dt}&=\frac{3}{2}(\frac{du_{\mathrm{s}\alpha}^{-}}{dt}i_{\mathrm{s}\alpha^{-}}+\frac{du_{\mathrm{s}\beta}^{-}}{dt}i_{\mathrm{s}\beta^{-}}+\frac{di_{\mathrm{s}\alpha}^{-}}{dt}u_{\mathrm{s}\alpha^{-}}+\frac{di_{\mathrm{s}\beta}^{-}}{dt}u_{\mathrm{s}\beta^{-}})\\\frac{dQ_{22}}{dt}&=\frac{3}{2}(\frac{du_{\mathrm{s}\beta}^{-}}{dt}i_{\mathrm{s}\alpha^{-}}-\frac{du_{\mathrm{s}\alpha}^{-}}{dt}i_{\mathrm{s}\beta^{-}}+\frac{di_{\mathrm{s}\alpha}^{-}}{dt}u_{\mathrm{s}\beta^{-}}-\frac{di_{\mathrm{s}\beta}^{-}}{dt}u_{\mathrm{s}\alpha^{-}}).\end{aligned}\tag{20}$$

Substituting (1), (2) and (4) into (20), the dynamics of the instantaneous active and reactive powers P_{11} and Q_{11} can be obtained as follows,

$$
\begin{aligned}
\frac{dP_{22}}{dt} &= \omega_1 Q_{22} - \frac{R}{L}P_{22} + \frac{3}{2L}[|\boldsymbol{U}_{\mathrm{s}}^{-}|^2 - (v_{\mathrm{c}\alpha}^{-}u_{\mathrm{s}\alpha}^{-} + v_{\mathrm{c}\beta}^{-}u_{\mathrm{s}\beta}^{-})] \\
\frac{dQ_{22}}{dt} &= \omega_1 P_{22} - \frac{R}{L}Q_{22} - \frac{3}{2L}(v_{\mathrm{c}\alpha}^{-}u_{\mathrm{s}\beta}^{-} - v_{\mathrm{c}\beta}^{-}u_{\mathrm{s}\alpha}^{-}).
\end{aligned}
\tag{21}
$$

Define U_{P}^{-} and U_{Q}^{-} as the VMR inputs for negative sequence controller which can be expressed as,

$$
\begin{aligned}
U_{\mathrm{P}}^{-} &= v_{\mathrm{c}\alpha}^{-}u_{\mathrm{s}\alpha}^{-} + v_{\mathrm{c}\beta}^{-}u_{\mathrm{s}\beta}^{-} \\
U_{\mathrm{Q}}^{-} &= v_{\mathrm{c}\alpha}^{-}u_{\mathrm{s}\beta}^{-} - v_{\mathrm{c}\beta}^{-}u_{\mathrm{s}\alpha}^{-}.
\end{aligned}
\tag{22}
$$

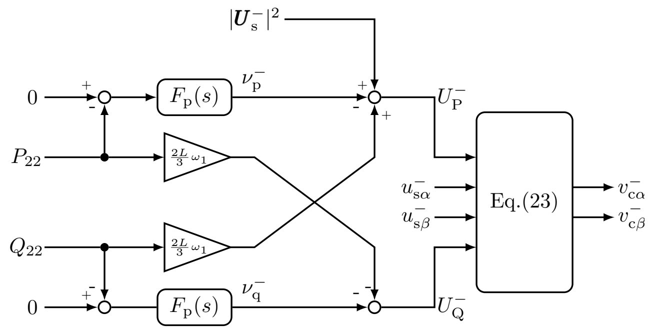

Fig. 2. Proposed UVM-DPC for negative sequence regulation.

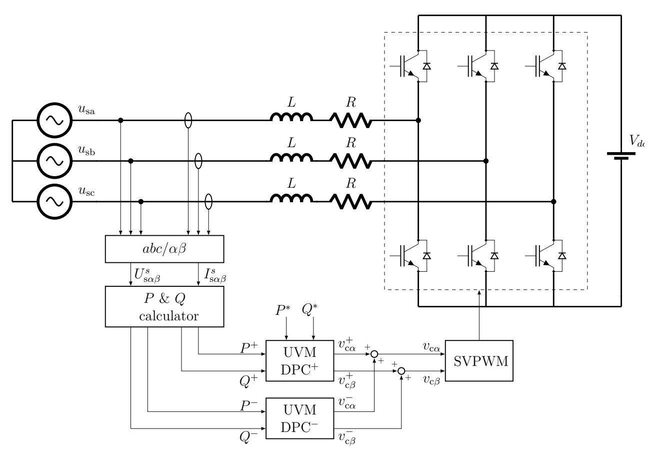

Fig. 3. Scheme diagram of improved GVM-DPC based dual control strategy for unbalanced network condition.

By manipulating (21) and (22), the VMR inputs can be also expressed as,

$$
\begin{aligned}
U_{\mathrm{P}}^{-} &= \nu_{\mathrm{P}} + \frac{2L}{3}\omega_1 Q_{22} + |\boldsymbol{U}_{\mathrm{s}}^{-}|^2 \\
U_{\mathrm{Q}}^{-} &= \nu_{\mathrm{Q}} - \frac{2L}{3}\omega_1 P_{22},
\end{aligned}
\tag{23}
$$

TABLE I
PARAMETERS OF THE SIMULATED SYSTEM

Rated power	2 MW
Line-to line voltage (rms)	690 V
frequency f	50 Hz
R (ohm)	0.00002
L_{s} (mH)	0.4
$K_{\mathrm{p,P}}$	0.3
$K_{\mathrm{i,P}}$	5
$K_{\mathrm{p,Q}}$	0.3
$K_{\mathrm{i,Q}}$	5

where ν_{P} and ν_{Q} are the new control inputs. The power regulation system can be transformed into a LTI system as,

$$
\begin{aligned}
\nu_{\mathrm{P}}^{-} &= \frac{2L}{3}(\frac{dP_{22}}{dt} + \frac{R}{L}P_{22}) \\
\nu_{\mathrm{Q}}^{-} &= \frac{2L}{3}(\frac{dQ_{22}}{dt} + \frac{R}{L}Q_{22}).
\end{aligned}
\tag{24}
$$

In this paper, the parameters of negative sequence controller are chosen to be the same to positive sequence controller as $K_{\mathrm{p,P}} and K_{\mathrm{i,P}}$ respectively. PI controllers $F_{\mathrm{p}}(s)$ for both components are designed as,

$$
\begin{aligned}
\nu_{\mathrm{P}}^{-} =& K_{\mathrm{p,P}}(P_{22}^{*} - P_{22}) + K_{i,P}\int(P_{22}^{*} - P_{22})dt \\
\nu_{\mathrm{Q}}^{-} =& K_{\mathrm{p,Q}}(Q_{22}^{*} - Q_{22}) + K_{i,Q}\int(Q_{22}^{*} - Q_{22})dt.
\end{aligned}
\tag{25}
$$

Using the inversion of (22), voltage vector reference value of the negative sequence controller can be calculated as follows,

$$
\begin{cases}
v_{\mathrm{c}\alpha}^{-} = \dfrac{u_{\mathrm{s}\alpha}^{-}U_{\mathrm{P}}^{-} + u_{\mathrm{s}\beta}^{-}U_{\mathrm{Q}}^{-}}{|\boldsymbol{U}_{\mathrm{s}}^{-}|^2} \\
v_{\mathrm{c}\beta}^{-} = \dfrac{u_{\mathrm{s}\beta}^{-}U_{\mathrm{P}}^{-} - u_{\mathrm{s}\alpha}^{-}U_{\mathrm{Q}}^{-}}{|\boldsymbol{U}_{\mathrm{s}}^{-}|^2}.
\end{cases}
\tag{26}
$$

The positive sequence controller and negative sequence controller are shown in Fig.1 and Fig.2 respectively. It should be noted that the plus-minus sign of power compensation terms are different between two controllers.

IV. Simulation Results

Simulation results of the proposed D-GVM-DPC strategy for SVPWM converter is carried out by using MATLAB/Simulink. The scheme of the implemented model is shown in Fig.3. The requirements for converters are designed as follows, obtaining the sinusoidal currents; unity power factor; low ripple of active & reactive powers. The parameters of simulated system are proposed in Table I. The power reference are set as $P_{ref} = 1MW$ and $Q_{ref} = 0Mvar$. To verify the effectiveness of proposed strategy, four different controllers are built and compared in this section. Controllers to be compared including classic VOC based PI controller, general VOC based dual controller, GVM-DPC proposed in [4] and proposed D-GVM-DPC based dual control strategy. The simulation time step is set to 5 μs and the sampling frequency is set to 10 kHz.

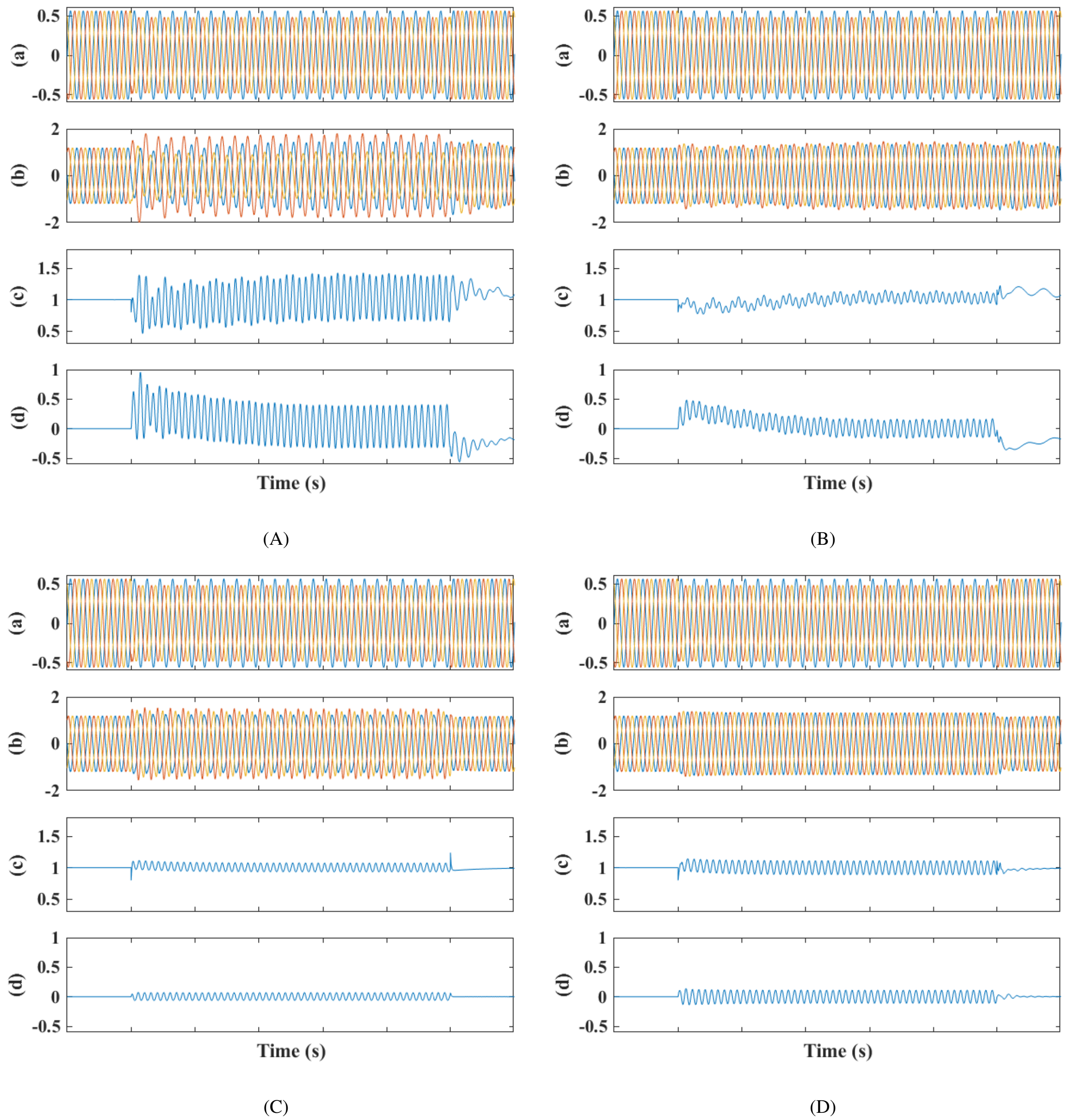

Fig. 4. Responses of currents and active power & reactive power under 20% grid voltage dips in phase A and phase B. (a) Three-phase voltages(kV). (b) Three-phase currents (kA). (c) Active power (MW). (e) Reactive power (MVar). (A) Classic VOC based PI controller. (B) General dual-control strategy for VOC. (C) GVM-DPC controller proposed in [4]. (D) Proposed D-GVM-DPC strategy

Dynamic responses of currents, active and reactive powers between four controllers under two phase network voltage dips at 20% are presented as shown in Fig. 4. The ripples of active and reactive powers of DPC based controllers shown in (C) and (D) are much lower than that of general VOC based controllers (A) and (B). Comparing (A) and (B) in Fig.4, it can be concluded that general dual control strategy for VOC can effectively restrain the active and reactive power ripples. as shown in Fig.4 (C), the original proposed GVM-DPC already has a pretty satisfied power dynamics. The proposed D-GVM-DPC however, make the power dynamics a slight change for the worse. But the dynamics are still better than VOC strategies.

Current spectra of phase A are shown in Fig.5 (A)-(D) with different control strategies under 20 % network voltage dips in phase A and phase B. The dual control strategy for VOC can effectively improve the power ripples and unbalances of currents, but there is almost no distinction of their Total Harmonic Distortion (THD). The THD of original GVM-DPC under unbalanced grid voltage is 11.31%, which is higher than commonly required value (5%) for grid operation. On the contrary, the current THD of the converter using proposed

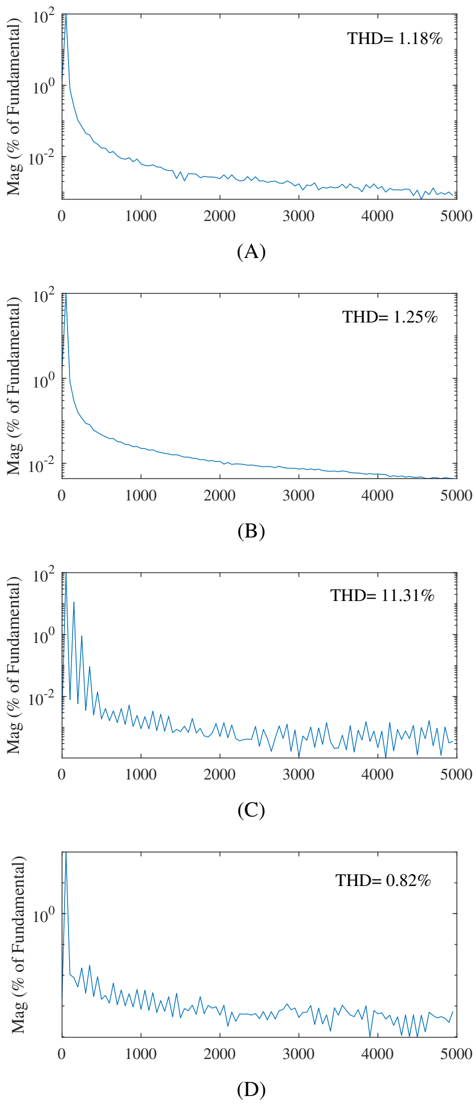

Fig. 5. Current harmonic spectra under 20% unbalanced voltage condition. (A) Classic VOC based PI controller. (B) General dual-control strategy for VOC. (C) GVM-DPC controller proposed in [4]. (D) Proposed D-GVM-DPC strategy

D-GVM-DPC is much lower than that of original GVM-DPC and grid requirement, the performance is even better than VOC based controllers. Thus, the proposed method is verified.

V. Conclusion

Currently, the existing methods for DPC under unbalanced network conditions are mainly modifying the original power references by adding compensations. In this paper, a D-GVM-DPC control strategy for grid-connected VSC under unbalanced network is proposed. The concept of D-GVM-DPC is by separately regulating the positive power sequence and negative power sequence to restrain current ripples under voltage distortions. The mathematical model of VSC under unbalanced network condition is fully discussed and the principles and design of proposed method is explained in detail. The effectiveness of D-GVM-DPC is verified by the simulation results.

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